Multiple stars: designation, catalogues, statistics

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Summary. Discussion of the designation of multiple-star components leads to a conclusion that, apart from components, we need to designate systems and centers-of-mass. The hierarchy is coded then by simple links to parent. This system is adopted in the multiple star catalogue, now available on-line. A short review of multiple-star statistics is given: the frequency of different multiplicities in the field, periods of spectroscopic sub-systems, relative orbit orientation, empirical stability criterion, and period-period diagram with its possible connection to formation of multiple stars.

1 Designation of multiple stars

Actual designations of binary and multiple stars are historical, non-systematic and confusing. Future space missions like GAIA, ongoing searches for planets, and other large projects will greatly increase the number of known multiple stars and components, making it urgent to develop a coherent and unambiguous designation scheme. Recognizing this need, IAU formed a special group that held its meetings in 2000 and 2003. As a result, IAU adopted the designation system developed for the Washington Multiple Star Catalogue (WMC) [5], an extension of the current designations in the Washington Double Star Catalogue (WDS) [7]. Old WDS designations will not change (to avoid further confusion), new component names will be constructed hierarchically as sequences of letters and numbers, e.g. Ab2. The designations reflect hierarchical structure of multiple systems, but only to a certain extent. Future discoveries of components at outer or intermediate levels of hierarchy and the constraint of fixed designations will inevitably lead to situations where names do not reflect the true hierarchy, which has then to be coded separately.

In the future, many components of multiple systems will be resolved into sub-systems, so that A will become Aa and Ab, for example. Nevertheless, current designations of these components (or rather *super-components*, as they contain more than one star) will not become obsolete, because past and future measurements of these entities as a whole will still refer to the super-component names such as "A" in our example. It turns out that the concept of super-components is crucial to the whole problem. Once each super-component has its own designation, unique within each multiple system, we can code hierarchies by simple reference to parent (Fig. 1).
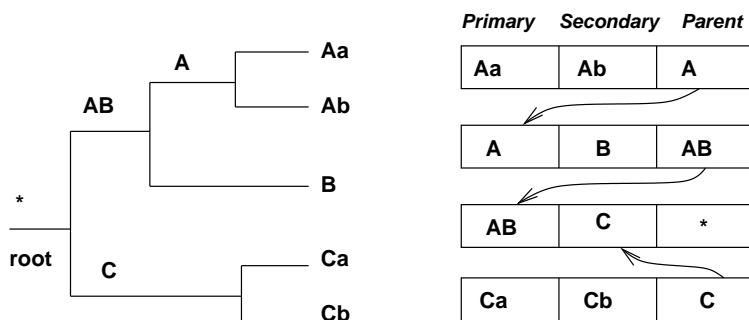
Fig. 1. Hierarchical structure of a quintuple system and its coding by reference to parent. Given the components designations and references to parent (right), the hierarchical tree (left) can be constructed automatically.

The WMC designation system extended to normal components and super-components is thus logical and flexible, permitting to accommodate new discoveries. Its application is not free of ambiguity, however, so that a common center (or clearing house) will still be required. The WMC itself will hopefully play this role.

2 Multiple-star catalogues

Although multiple stars are quite common, this fact is not reflected in the catalogues. A researcher wishing to study large samples of multiple stars has to compile his own lists or use the lists published by others, e.g. [4, 2]. It is equally possible to extract multiple stars from binary catalogues. The current 9-th catalogue of spectroscopic binary orbits, SB9[1] [9], contains multiplicity notes and visual-component designations. Many visual multiples are listed in the WDS [7], but the physical relation between their components has not been studied systematically, many are simple line-of-sight projections (optical).

The Multiple Star Catalogue (MSC) [11] is an attempt to create and maintain a list of *physical* systems with 3 or more components. The MSC is essentially complete for "historical" multiple systems known before 1996, with the exception of visual multiples (only a fraction of WDS multiples have been checked for physical relation). The completeness of the MSC (1024 systems as of July 2005) is less evident with respect to new discoveries. An on-line interface to the MSC became available recently[2]. The MSC contains estimates of component masses and orbital parameters, essential for statistical studies, e.g. [16]. Several observing programs have used the MSC to create their samples. The new designation system is now implemented in the MSC, hierarchical trees like that in Fig. 1 are displayed on-line.

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[1]http://sb9.astro.ulb.be
[2]http:/www.ctio.noao.edu/~atokovin/stars/

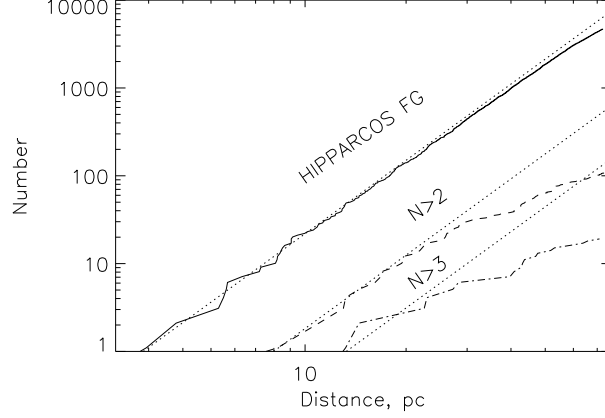# 3 Statistics of multiple stars

Fig. 2. Completeness of the multiplicity knowledge: number of stars and systems of spectral types F and G ($0.5 < B - V < 0.8$) within given distance. Full line: objects in the HIPPARCOS catalogue follow reasonably well the expected cubic law (dotted line). Dashed line: F- and G-type dwarfs with 3 or more companions from MSC also follow the cubic law, but only up to a distance of 30 pc (1/12th of all stars have 3 or more components). At 50 pc, the estimated completeness is only 40%. Dash-dot: quadruples and higher multiplicities, still very incomplete.

Frequency of multiple stars. The values of multiplicity fraction given in the literature are often confusing because of different definitions of this parameter. Let n_k be the fraction of systems with exactly k components, and a_k – the fraction of systems containing at least k components (i.e. counting higher multiplicities as well). Evidently, $n_k = a_k - a_{k+1}$. Batten [1] defines the multiplicity ratio $f_k = a_k/a_{k-1}$ and argues that $f_k \sim 0.25$ for $k \geq 3$. This estimate has been confirmed with a larger sample from the MSC [12]. It follows immediately that $n_k = a_k(1 - f_{k+1})$.

Duquennoy & Mayor [3] (DM91) count all binary pairings, irrespectively of their hierarchy. A *companion star fraction* $CSF = n_2 + 2n_3 + 3n_4 + ... = 0.62$ can be inferred from their Fig. 7. From Fig. 2, we estimate $a_3 \approx 1/12$ (a higher estimate $a_3 = 0.2 - 0.25$ has been given in [14]). Assuming $f_k = 0.25$, we calculate n_3, n_4, n_5, etc., and evaluate the contribution to the CSF from pairings in multiple stars as $2n_3 + 3n_4 + 4n_5 + ... = 0.26$. Hence, the fraction of pure binaries in the DM91 sample should be $n_2 = 0.62 - 0.26 = 0.36$, the fraction of systems that are at least binary is $a_2 = n_2 + a_3 = 0.44$, and the fraction of higher hierarchies with respect to binaries is $f_3 = a_3/a_2 = 0.19$. A smaller number $f_3 = 0.11 \pm 0.04$ (or $a_3 = 0.05$) can be derived directly from the DM91 data [12].

Short-period sub-systems and Kozai cycles. Spectroscopic binaries in the field seem to have a period distribution that smoothly rises toward longer periods in the range from 1 to 1000 d, according to several independent studies [3]. In contrast, the distribution of periods of spectroscopic sub-systems in multiple stars shows a maximum at periods below 7 d [15]. This "feature" is too sharp to be explained by selection effects, and the transition period is suspiciously similar to the cutoff period of tidal circularization. Dissipative Kozai cycles are the most likely mechanism that shortens periods of many (but not all) sub-systems below 7 d.

Relative orientation of orbits has been studied by Sterzik & Tokovinin [10]. Only in 22 cases the *visual* orbits of both outer and inner sub-systems are known. This extremely small sample has small ratios of outer-to-inner periods P_{out}/P_{in} because at long P_{out} the time coverage of existing visual data (about 200 yr) is still too short (in fact, many long-period orbits are uncertain or wrong), while orbits with short P_{in} are difficult to get for the lack of spatial resolution. The true ascending nodes of visual orbits are, generally, not identified, further complicating data interpretation. The advent of adaptive optics and long-baseline interferometry holds great promise in extending this sample significantly, mostly by resolving the inner (spectroscopic) sub-systems in visual binaries with known outer orbits, e.g. [8].

Despite current observational limitations, it is already clear that the inner and outer orbits are neither coplanar nor completely random. The directions of their orbital angular momenta are weakly correlated. Such correlation could be explained by dynamical decay of small stellar groups [10]. However, alternative explanations are possible, too. It will be extremely important to extend the studies of relative orbit orientation to larger samples and to start probing the orientations in different sub-groups.
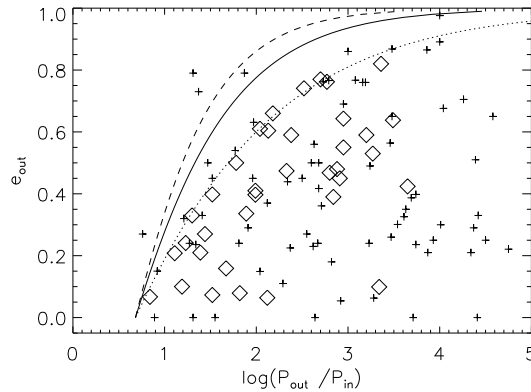

Fig. 3. Comparison of dynamical stability criteria with orbital parameters of the real systems: eccentricity of the outer orbit e_{out} (vertical axis) versus period ratio P_{out}/P_{in} (horizontal axis). The full line depicts the dynamical stability criterion of MA02, the dashed line is its modification proposed in [10], the dotted line is the empirical criterion.

Empirical stability criterion. Multiple systems where both inner and outer orbits are known offer rich possibilities for joint analysis of their orbital

parameters, e.g. checking the dynamical stability. Theoretical and numerical formulations of the stability criterion in the three-body problem have been offered by many authors and lead to similar results. I take the latest work of Mardling & Aarseth [6] (MA02) as representative and compare their stability criterion with 120 real systems from the MSC (Fig. 3). Some systems are, apparently, unstable. However, I can ignore both unreliable outer orbits with periods over 300 yr and inner periods shorter than 10d (likely affected by Kozai cycles), plotted as crosses in Fig. 3. The remaining systems (diamonds) nicely fall in the stability zone.

When outer orbits are nearly circular, the match between the data and the MA02 criterion is impressive: all systems indeed have $P_{\mathrm{out}}/P_{\mathrm{in}} > 4.7$. However, eccentric outer orbits deviate from the theoretical criterion in a systematic way. The *empirical stability criterion* [14] can be described by the relation $P_{\mathrm{out}}(1 - e_{\mathrm{out}})^3/P_{\mathrm{in}} > 5$, whereas all theoretical criteria lead to a similar relation with $(1 - e_{\mathrm{out}})^{2/3}$ instead of cube. The reason of this discrepancy remains a mystery.
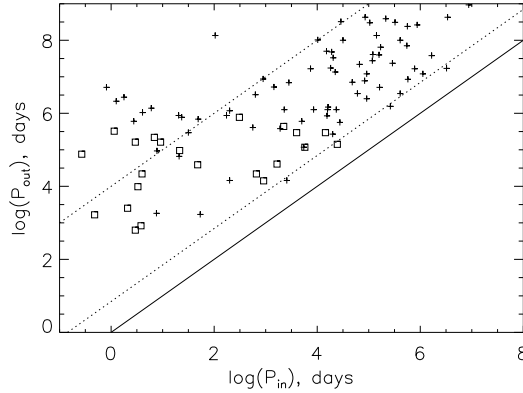

Fig. 4. Periods of inner (horizontal axis) and outer (vertical axis) sub-systems in a sample of nearby late-type multiples from the MSC. Systems where both periods are known from orbital solutions are plotted as squares, in the remaining systems (crosses) at least one period is estimated from the separation. The full line corresponds to equal periods, the dashed lines depict period ratios of 5 and 10 000.

Period-period diagram. What is a typical period ratio $P_{\mathrm{out}}/P_{\mathrm{in}}$ at adjacent hierarchical levels? Fekel [4] found it to be large, around 2000. In the MSC, we encounter all possible ratios allowed by the dynamical stability, i.e. greater than 5. However, systems at intermediate hierarchical levels often remain undiscovered, leading to wrongly estimated period ratios. By restricting the sample to nearby (within 50 pc) late-type stars, we reduce these errors and begin to see the true distribution of period ratios (Fig. 4).

The $P_{\mathrm{out}} - P_{\mathrm{in}}$ diagram reveals some features of multiple-star formation and evolution. Interestingly, period ratios larger than 10 000 are found only when $P_{\mathrm{in}} < 30$d, i.e. where inner periods were likely shortened by some

dissipative mechanism like Kozai cycles with tides. The only exception to this rule (the point at the top) is Capella, a pair of giants on a 100-d circular orbit in a quadruple system. It is very likely that all multiple stars have been formed with the period ratio $P_{\mathrm{out}}/P_{\mathrm{in}} < 10\,000$. Some inner periods were then shortened by tidal or other dissipative processes. In this perspective, Capella had a rather eccentric initial orbit with a period of few tens of years which has been shortened and circularized when its components became giants.

4 Conclusions

Cataloguing of multiple systems, however boring it might seem, offers interesting insights into formation and evolution of stars. New powerful observing techniques (adaptive optics, interferometry, precise radial velocities) should now be applied to large stellar samples in order to "fix" the multiplicity statistics in the solar neighborhood and beyond.

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